an investigation into the effects of vibration on the bonding and compressive strength of full-depth bridge deck repairs

have no detrimental effects on either concrete-steel bond strength or compressive strength in full-depth bridge deck repairs, so long as low slump concrete is used. This conclusion is based on the results of experiments using vibrations that match values obtained from field measurements. Variations in concrete cover, reinforcing bar sizes, and slump were investigated.

Traffic-Induced Vibrations and Bridge Deck Repairs

by Shraddhakar Harsh and David Darwin

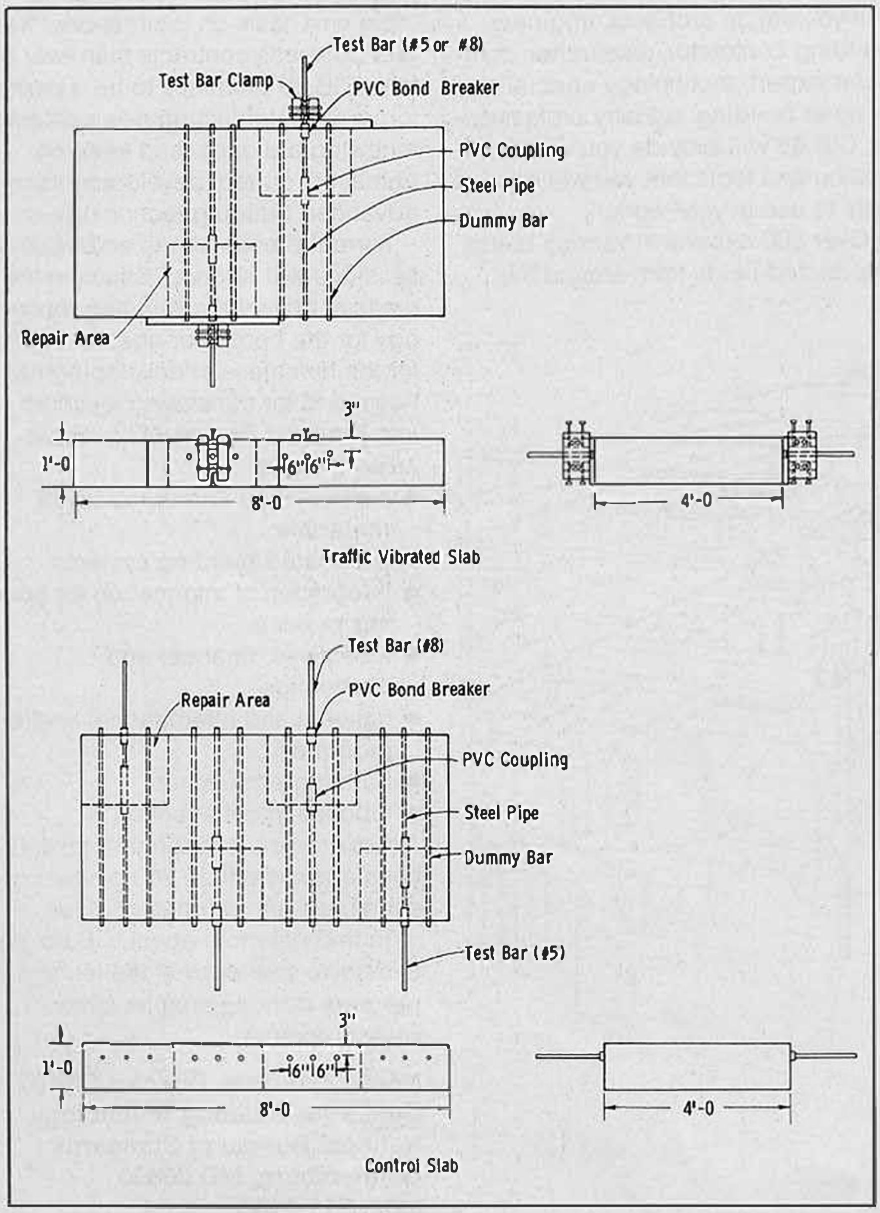

Fig. 1—Two different test slabs, one vibrated and one not, were used in these investigations. (in. × 25.4 = mm; ft × 0.305 = m)

What is the effect of allowing traffic to continue to travel over a bridge during repair operations? Over the years there has been considerable concern about the advisability of this practice. While it is generally agreed that vibration assists in the consolidation of plastic concrete,[1,2,3,4] special concern has centered around the effects of traffic-induced vibrations if the vibrations continue while the concrete repair undergoes its initial set.[5,6]

In spite of the importance of this question, only a limited number of studies have been carried out.[5,6,8] To date, the bulk of the evidence indicates that maintaining traffic during concrete placement does not lower the quality of the repairs.[7] Data is incomplete, however, and one of the studies[8] did not provide a true comparison between traffic-vibrated and nonvibrated repairs since test specimens of different size, reinforcement, curing conditions, and concrete strength were used.

Keywords: bond (concrete to reinforcement); bridge decks; compressive strength; concrete construction; consolidation; cover; **moving loads;** pullout tests; **reinforced concrete; repairs; vibration.**

TABLE 1—Bond test variables and results

Bar size	Slump (in.)	Cover (in.)	Embedment length (in.)	Avg. bond strength-V* (kips)	Avg. bond strength-C† (kips)	ACI, AASHTO load (kips)
#5	1.5	3.0	5	18.1	18.7**	7.7
#8			9	43.0	43.0	16.6
#5	4.5	3.0	4	17.4	17.5	6.1
#8			9	45.4	43.0	16.4
#5	1.5	3.0	4	13.6	12.5	6.1
#8			9	41.0	36.0	15.3
#5	4.0	1.5	4	9.5	10.3	6.1
#8			9	27.0	25.2	16.0
#5	7.5	1.5	4	11.9	12.6	6.1
#8			9	26.5	27.3	14.8

*V = Traffic vibrated specimen
†C = Control
**Pullout force exceeded yield strength
in. x 25.4 = mm
kip x 4.45 = kN
Bar sizes: #5 = 16 mm; #8 = 25 mm

This study focuses on the effects of simulated traffic-induced vibrations on concrete-steel bond strength and concrete compressive strength in full-depth bridge repairs. The effects of concrete slump, bar size, and cover are also considered. The results are compared with predictions of the AASHTO Bridge Specifications[9] and the ACI Building Code,[10] and recommendations are made.

Experimental investigation

To study the effects of traffic-induced vibrations on bridge deck repairs, a simply supported steel bridge frame was constructed in the laboratory. Reinforced concrete deck specimens were bolted to the frame to obtain full composite action. These deck slabs contained block-outs in which "repairs" were made. In addition, steel cylinder molds were bolted to the slabs to determine the effect of the vibrations on compressive strength. Following the placement of plastic concrete, the bridge frame was subjected to vibrations of an amplitude and frequency typical of those occurring on highway bridges; nonvibrated, control specimens were used for comparison. Additional details of this investigation are presented in References 11 and 12.

Test specimens. Fifteen 4 x 8 ft (1.2 x 2.4 m) shallow deck specimens with a total depth of 12 in. (305 mm) (Fig. 1) were used to study the effects of vibrations on bond strength. The slab specimens were fabricated in groups of three: two were subjected to simulated traffic-induced vibrations, while the third served as a nonvibrated, control slab. Two top covers were also studied: 1.5 and 3 in. (38 and 76 mm).

The slab specimens were cast with 23 x 18 in. (584 x 457 mm) blockouts, as shown in Fig. 1. The vibrated slabs had two block-outs, while the control slabs had four block-outs. With each of the slab groups, one vibrated slab contained #5 (16 mm) bars, while the other contained #8 (25 mm) bars; the reference slab had both #5 and #8 (16 and 25 mm) bars. Dummy bars (not tested) were placed 6 in. (152 mm) on either side of the test bars.

Full information on the test variables, including embedment depth, cover, bar size, and slump, is presented in Table 1.

TABLE 2—Concrete mix proportions (in lb/yd³) and properties

	Test group	w/c ratio	Cement	Water	Aggregate Fine*	Aggregate Coarse†	Slump in.	Air %	Strength psi
Ready-mixed for slab	1	0.44	591	235	1470	1482	4	‡	5160
	2	0.46	579	265	1453	1441	1¼	4½	‡
	3	0.44	555	244	1455	1545	4¼	10½	2960
	4	0.44	555	244	1455	1536	3¼	5½	5160
	5	0.44	555	244	1455	1536	5½	7½	3760
Ready-mixed for repairs	1	0.46	579	267	1448	1449	1½	5	3480
	2	0.49	614	300	1413	1425	4½	2	3410
	3	0.44	555	244	1455	1536	1½	7	2960
	4	0.44	564	248	1491	1455	4	7	3230
	5	0.44	680	300	1300	1440	7½	7½	3000
Laboratory mixed	1	0.44	680	300	1300	1440	7¾	5½	3770
	2	0.44	645	284	1375	1438	5	4½	3870
	3	0.44	555	244	1536	1435	1½	5	3930

*Kansas river sand
†Crushed limestone
‡Value was not recorded
lb/yd³ x 0.593 = kg/m³
in. x 25.4 = mm
psi x 6.895 = kPa

Material properties.

Concrete: Air entrained concrete was supplied by a local ready-mixed plant for both the initial placement and the repair of the test specimens. Type I cement and ¾ in. (19 mm) nominal maximum size coarse aggregate was used. Laboratory mixed concrete was used to obtain additional information about the effects of the vibration on compressive strength. Mix proportions, and aggregate

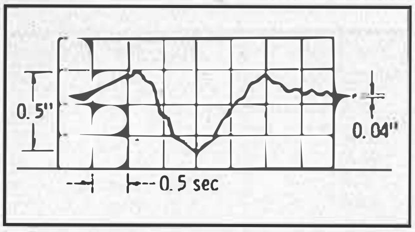

Fig. 2—The wave pattern for the simulated traffic-induced vibration shows the superimposed truck vibration on the more typical auto-induced vibration. (in. x 25.4 = mm)

and concrete properties are summarized in Table 2.

Steel: ASTM A615, Grade 60 reinforcing bars were used for all tests.

Preparation of specimens. When the blocked-out slabs had gained a strength of 3000 psi (20.7 MPa), the forms were stripped and the areas to be "repaired" were cleaned with a water blaster [rated at 2000 psi (13.8 MPa)] until all of the laitence and carbonation had been removed. Two slabs were then moved to the bridge frame and bolted in place. The nonvibrated slabs remained on the floor.

Repair concrete was placed within 24 hr of water blasting. The concrete was allowed to rest for 10 min and then was consolidated using a hand held electric vibrator. The slabs were screeded and floated by hand.

Coincident with the placement of the repair concrete, four 6 x 12 in. (152 x 305 mm) cylinder molds were filled and then attached to the slabs on the bridge frame. Four control cylinders were also made. These cylinders were consolidated using a laboratory vibrator for low slump specimens [less than 3 in. (76 mm)] and rodded for higher slumps. Ten minutes after the concrete had been floated, the simulated traffic-induced vibrations were started. The vibrations continued for a period of 30 hr.

The two vibrated test slabs were spaced equally on either side of the center line of the bridge frame. Linear variable differential transformers (LVDT) were placed at the slab center lines and used to monitor the amplitude of the vibrations. One LVDT provided feedback for the system, insuring that the desired movement was obtained at the center of the slab. A closed-loop servo-hydraulic actuator was used to drive the system.

Vibrations imposed on the test specimens were selected to match those measured in the field.[6,13,14] Throughout the 30 hr period, the slab center lines were subjected to a sinusoidal vibration of 0.04 in. (0.5 mm) peak-to-peak amplitude, at a frequency of 4.0 Hz. To simulate intermittent truck traffic, a single excursion with static amplitude of 0.5 in. (+0.125 in., −0.375 in.) [13mm (+3 mm, −10 mm)] and frequency of 0.5 Hz, was superimposed once every four minutes upon the small amplitude vibrations (Fig. 2). The vibrations correspond to a peak particle acceleration of 14 $in./sec^2$ and a peak particle velocity of 1.4 in./sec (356 mm/sec^2 and 36 mm/sec).

Vibrations were terminated after 30 hr. The slabs were left in place until the repair concrete had attained a strength of approximately 3000 psi (20.7 MPa) and were then removed for testing.

Test procedure. The pullout apparatus was the same as used by Donahey and Darwin [15,16] and was designed so that both the test bars and the surrounding concrete in the modified cantilever slab specimens would be placed in tension, as would occur in a bridge deck. Prior to testing, pre-existing settlement and shrinkage cracks were marked on the surface of the repairs and photographed.

Each group of three slabs was tested within a 10-hr period, at ages ranging from 4 to 10 days. The test cylinders of repair concrete, and cylinders from the surrounding slab concrete, were tested immediately following the pullout tests.

Results and observations.

Pretest observations: No settlement cracks were observed over bars with a 3 in. (76 mm) cover (Groups 1, 2 and 3). Settlement cracks *were* observed in both groups of specimens with a 1½ in. (38 mm) cover (Groups 4 and 5); these cracks followed both test and dummy bars within the repaired area. Also, Group 5 [1½ in. (38 mm) cover, 7½ in. (191 mm) slump] exhibited shrinkage cracks. Crack intensity was approximately the same on both the vibrated and nonvibrated slabs.

Bond Strength: In testing for bond strength the failure mode was dependent upon cover and bar size (see Table 1). The #5 (16 mm) bars with 1½ in. (38 mm) cover and all of the #8 (25 mm) bars failed by longitudinal splitting. Pullout of the #8 (25 mm) bars was also accompanied by significant transverse cracking. The #5 (16 mm) bars with 1½ in. (38 mm) cover exhibited very little transverse cracking and the #5 (16 mm) bars with 3 in. (76mm) cover exhibited no surface cracking upon pullout.

Compressive Strength: A set of four traffic vibrated and four control cylinders were cast with each of the last three groups of repair specimens from the ready-mixed concrete. Three additional sets, of three vibrated and three control cylinders each, were also tested from the laboratory mixed concrete. The results of these tests are summarized in Table 3. Upon crushing, the vibrated and nonvibrated cylinders exhibited a typical conical failure, with the exception of one high slump [7½ in. (191mm)] vibrated cylinder, which crushed locally at the top end. Low slump concrete developed a higher strength in the vibrated cylinders, while high slump concrete gave a higher strength in the control cylinders.

Evaluation of results

The test results are used to examine the effects of traffic induced-vibrations on both bond strength and compressive strength. The effects of slump, bar size, and cover on bond strength and of slump on compressive strength are considered in con-

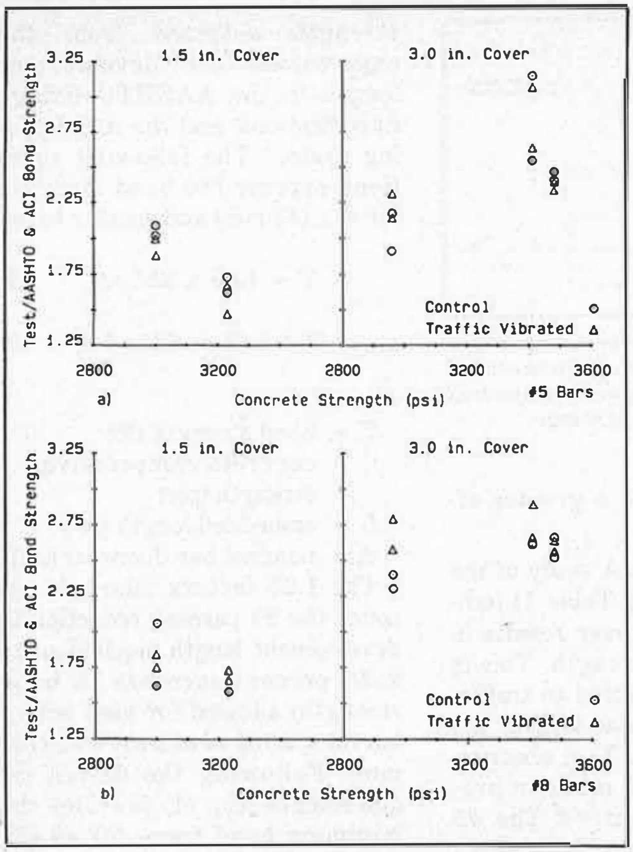

Fig. 3—*The bond strength relationship between traffic-vibrated and control samples was shown to be a function of slump, cover, and bar size.*

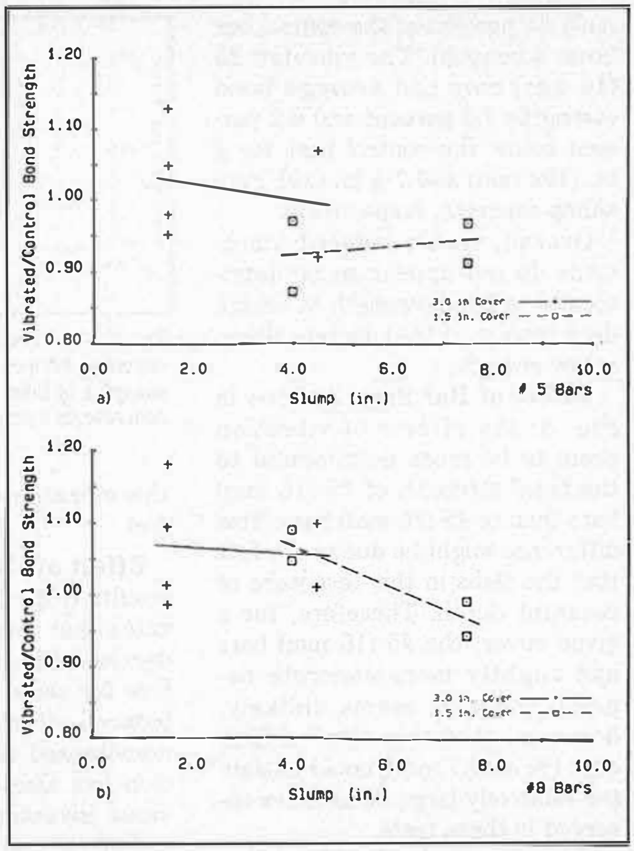

Fig. 4—*The measured bond strength for variations of concrete strength, cover, and bar size is compared to the bond strength predicted by AASHTO and ACI standards.*

junction with the effects of the vibrations. The bond strengths obtained are also compared with those predicted by the AASHTO Bridge Specifications[9] and the ACI Building Code.[10]

Bond strength. The bond strength results are summarized in Fig. 3 and 4. Fig. 3 shows the relationship between traffic-vibrated and control bond strength as a function of concrete slump, bar size, and cover. Fig. 4 compares the individual bond strengths to the values predicted by AASHTO[9] and ACI[10] as a function of concrete strength, bar size, and cover.

The results indicate the *relative* effects of simulated traffic-induced vibration; the strengths represent carefully fabricated laboratory specimens. For practical application, the relative changes in strength (both increases and decreases) should be superimposed upon bond strengths as they exist in the field.

Effect of Slump: Fig. 3 illustrates the importance of slump in determining whether traffic-induced vibrations are detrimental to concrete-steel bond in bridge deck repairs. The points plotted in Fig. 3 represent the ratio of the bond strengths of the individual vibrated bars to the average value for the control bars for a particular slab group.

For low to medium slump concrete with a 3 in. (78 mm) cover over the bars, the traffic-induced vibrations increased the average bond strength by values ranging from 0.1 percent for #5 (16 mm) bars with 4½ in. (114 mm) slump concrete, up to 14.1 percent for #8 (25 mm) bars with 1½ in. (38 mm) slump concrete. The large scatter exhibited by the results is typical of bond tests, with individual values ranging from a decrease in bond strength of 9 percent to an increase of 18 percent.

The two control #5 (16 mm) bars in the first group yielded. Had these bars been higher in strength, they would have provided a somewhat higher bond strength. In that case, the slope of the line for the #5 (16 mm) bars with 3 in. (76 mm) cover would have been flatter than show in Fig. 3a.

The bars with 1½ in. (38 mm) cover and high slump concrete also exhibit the effect of slump on bond strength. For the #8 (25 mm) bars, the average bond strength of the traffic-vibrated bars show a 7.1 percent increase at a 4 in. (191 mm) slump and a 3.7 percent decrease with a 7½ in. (191 mm) slump concrete, when compared to the control bars.

The same trend is not observed for the #5 (16 mm) bars, because one of the two vibrated bars for the 4 in. (102 mm) slump concrete had an especially low strength (only 88 percent of the control bar bond strength). The vibrated #5 (16 mm) bars had average bond strengths 7.5 percent and 6.2 percent below the control bars for 4 in. (102 mm) and 7½ in. (191 mm) slump concrete, respectively.

Overall, traffic-induced vibrations do not appear to be detrimental to bond strength in bridge deck repairs, if the concrete slump is low enough.

Effect of Bar Size: As seen in Fig. 3, the effects of vibration seem to be more detrimental to the bond strength of #5 (16 mm) bars than to #8 (25 mm) bars. This difference might be due to the fact that the slabs in this test were of constant depth. Therefore, for a given cover, the #5 (16 mm) bars had slightly more concrete beneath them. It seems unlikely, however, that this small difference [3/8 in.(9.7 mm)] could explain the relatively large differences observed in these tests.

It is more likely that the difference in the results is due to a difference in failure mode, since at pullout the #8 (25 mm) bars tended to crack more concrete through the depth of the slabs. In that way, the #8 (25 mm) bars were able to use the strength of the higher density concrete in the lower portions of the vibrated slabs.

Pullout of the #5 (16 mm) bars was dependent only upon the concrete in the local vicinity of the bar. Since the bars were all near the upper portion of the slab, the higher degree of bleeding and local settlement cracking caused by the vibrations had a greater effect.

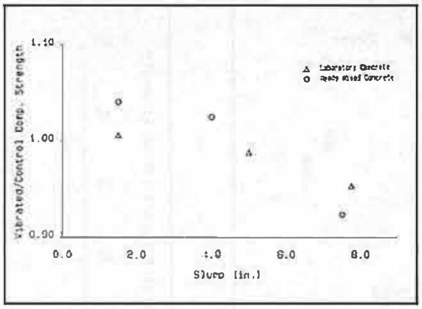

Fig. 5—The compressive strength relationship between vibrated and control samples of laboratory and ready-mixed concrete as a function of slump.

Effect of Cover: A study of the results (Fig. 4 and Table 1) indicates that lower cover results in decreased bond strength. This is true for slabs subjected to traffic-induced vibrations as well as for nonvibrated slabs. This observation has also been made in previous investigations.[15-19] The #5 and #8 (16 and 25 mm) bars with a 1½ in. (38 mm) cover had average bond strengths equal to 73 and 63 percent, respectively, of the bond strength of bars with a 3 in. (76mm) cover.

A study of Fig. 3 leads to the conclusion that bars with low cover are affected more by the vibrations than bars with a high cover. Based on the limited number of tests, however, this statement should be made with caution.

Design Equations: In Fig. 4, the test results are compared to the predicted values of bond strength obtained from the expressions for development length in the AASHTO Bridge Specifications[9] and the ACI Building Code.[10] The following equations express the bond strength for #11 (35 mm) and smaller bars:

$$T = 1.25 \times 25L\sqrt{f'_c} \qquad (1)$$

$$T = 1.25 \times 625\pi\, Ld_b \qquad (2)$$

where

T = bond strength (lb)
f'_c = concrete compressive strength (psi)
L = embedded length (in.)
d_b = nominal bar diameter (in.)

The 1.25 factors take into account the 20 percent reduction in development length (equivalent to a 25 percent increase in bond strength) allowed for bars with a lateral spacing of at least 6 in. (152 mm). Following the design requirements, Eq. (1) provides the minimum bond force for #8 (25 mm) bars, while Eq. (2) provides the minimum bond force for #5 (16 mm) bars.

As observed in Fig. 4, the AASHTO and ACI requirements are conservative for all of the bars tested, with no individual test result below 1.45 times the predicted value. The results for the #8 (25 mm) bars are more closely grouped than for the #5 (16 mm) bars, because Eq. (1), which is used for the #8 bars, takes into account concrete strength, while Eq. (2), which is used for the #5 bars, does not.

It should be emphasized that all of the bars in these tests were tightly secured to the deck slabs and supporting forms prior to subjecting the decks to vibration, and that these results do not pertain to cases in which the bars may be subjected to some movement relative to the supporting structure while the concrete is setting.

Compressive strength. Table 3 and Fig. 5 illustrate the effect of the simulated traffic-induced vibrations on the compressive strength of standard 6 x 12 in.

TABLE 3—Concrete compressive strengths from cylinder tests

Test group	Concrete source*	Slump in.	Number of cylinders tested†		Comp. strength (psi)		V/C ratio
			V	C	V	C	
3	RM	1½	4	4	3330	3200	1.041
4	RM	4	4	4	3310	3230	1.025
5	RM	7½	4	4	2770	3000	0.923
	LM	1½	3	3	3950	3930	1.005
	LM	5	3	3	3820	3870	0.987
	LM	7¾	3	3	3590	3770	0.952

*RM = Ready-mixed concrete; LM = Laboratory mixed concrete
†V = Traffic vibrated sample; C = Control sample
in. x 25.4 = mm
psi x 6.895 = kPa

(152 x 305 mm) cylinders. The ratio of vibrated to control cylinder strength is plotted as a function of concrete slump. Three data points represent ready-mixed concrete, while the other three represent concrete produced in the laboratory. The trend of the results is the same for both sources of concrete. The vibrations result in a small increase in strength for low slump concrete and a decrease in strength for high slump concrete.

The 1½ in. (38 mm) slump concrete was strengthened by the traffic-induced vibrations: 4.1 percent for the ready-mixed, and 0.5 percent for the laboratory concrete. Concrete with a slump of 4 in. (102 mm) (ready-mixed) and 5 in. (127 mm) (lab) was, respectively, strengthened 2.5 percent and weakened 1.3 percent by the vibrations. Concrete with a slump of 7½ in. (191 mm) (ready-mixed) and 7¾ in. (197 mm) (lab) underwent reductions in strength of 7.7 percent and 4.8 percent, respectively.

It is likely that the effects of traffic-induced vibration, as a function of slump, depend largely on the amount of segregation that occurs in the concrete. The higher slump concrete will have significantly more bleed water, which will rise in the test cylinders. The greater the agitation, the greater the bleed water that will rise to the top. Therefore, high slump concrete will have a layer of high water-cement ratio, low strength concrete at the upper end of the cylinder. During the compression test, this weaker concrete should dominate the cylinder strength.

On the other hand, the vibrations will help to consolidate the lower slump concrete, resulting in a denser material and a small increase in strength. Like the bond results, these tests suggest that traffic-induced vibrations are not detrimental to concrete strength, if the slump is below about 4 in. (102 mm).

Recommendations and conclusions

Traffic-induced vibrations appear to have no detrimental effect on either bond strength or compressive strength in bridge deck repairs, if high quality, low slump concrete is used. In fact, both bond strength and compressive strength appear to increase slightly for low slump concretes when vibrated.

As slump is increased, however, traffic-induced vibrations result in lower bond and compressive strengths. The results indicate that slumps in the range of 4 to 5 in. (100 to 130 mm) *can* be detrimental. Slumps in the range of 7 to 8 in. (175 to 205 mm) *are* detrimental when coupled with traffic-induced vibrations; for higher slump concretes, decreases of from 5 to 10 percent can be expected in both bond and compressive strengths.

Trends in bond strength are similar for both #5 and #8 (16 and 25 mm) bars, but the #5 (16 mm) bars are more adversely affected than the #8 (25 mm) bars. This may be due to differences in failure mode upon pullout.

Increased cover increases bond strength. The data are not extensive enough to provide firm conclusions about the effect of cover on the change in bond strength due to traffic-induced vibrations.

Based on the tests and analyses described in this paper, we recommend that traffic be allowed on bridge decks undergoing repair, with the stipulations that:

(1) low slump concrete [3 in. (76 mm) or less] is used for the repair, and
(2) reinforcement is securely fastened to the structure prior to concrete placement.

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